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DESCRIPTION

EXPOSURE APPARATUS WITH LASER DEVICE

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Technical Field

The present invention relates to an exposure apparatus including a laser device which generates ultraviolet light. More specifically, the present invention is preferably used as an exposure apparatus used in a photolithography process for manufacturing microdevices, such as semiconductor devices, image pickup devices (such as CCDs), liquid crystal display devices, plasma display devices, and thin-film magnetic heads.

Background Art

For example, an exposure apparatus used in a photolithography process for manufacturing a semiconductor integrated circuit optically reduces and projectively exposes a circuit pattern accurately rendered on a reticle (photomask) used as a mask, onto the photoresist-coated surface of a wafer as a substrate. In the exposure, shortening of an exposure-light wavelength (exposure wavelength) is one of the most simple and effective methods to reduce the minimum pattern size (resolution) on the wafer. Hereinbelow, a description will be made regarding conditions

that should be provided to configure an exposure light source, in addition to those for the implementation of the wavelength shortening of the exposure-light.

First, for example, an optical output of several watts is required. The optical output is required to reduce time necessary for exposure and transfer of an integrate circuit pattern and thereby to increase a throughput.

Second, when the exposure light is ultraviolet light having a wavelength of 300 nm or shorter, an optical material which can be used for a reflector member (lens) of a projection optical system is limited, and hence the difficulty increases for compensation of the chromatic aberration. For this reason, monochromaticity of the exposure light is required, and the spectral linewidth needs to be controlled to be about 1 pm or less.

Third, the timelike coherence increases in association with the reduction in the spectral linewidth. As such, when light having a narrow spectral linewidth (wavelength width) is emitted as it is, an unnecessary interference pattern called "speckle" is generated. Therefore, in the exposure light source, the spatial coherence needs to be reduced to suppress generation of the speckles.

One of conventional short-wavelength light sources satisfying these conditions is a light source using an excimer laser in which the laser oscillation wavelength itself is a short wavelength. Another conventional short-wavelength light source is of a type using harmonic waves generation of

an infrared or visible-range laser.

A KrF excimer laser (having a wavelength of 248 nm) is used as the above-described former short-wavelength light source. Currently, an exposure light source using a shorter-wavelength ArF excimer laser (having a wavelength of 193 nm) is under development. In addition, a proposal has been made for use of an F_2 laser (having a wavelength of 157 nm), which is one of excimer lasers. However, these excimer lasers are of a large scale, and the oscillatory frequency thereof is at about a level of several kHz in a present stage. This requires a per-pulse energy to be increased to increase a per-unit-time radiation energy. This arises various problems. For example, the transmittance of an optical component tends to vary because of so-called compaction and the like, complicated maintenance is required and hence costs are increased.

As the aforementioned latter method, there is a method that uses a secondary nonlinear optical effect of a nonlinear optical crystal, and thereby converts long wavelength light (infrared light or visible light) into ultraviolet light of short wavelength. For example, a publication ("Longitudinally diode pumped continuous wave 3.5W green laser", L. Y. Liu, M. Oka, W. Wiechmann and S. Kubota; Optics Letters, vol. 19, p189(1994)) discloses a laser source that performs a wavelength conversion of light emitted from a solid-state laser excited by a semiconductor laser beam. The publication regarding the aforementioned conventional

example describes a method of performing a wavelength conversion for a 1,064 nm laser beam generated by an Nd:YAG laser by using a nonlinear optical crystal, and thereby generates light of a 4th-harmonic-wave of 266-nm. The solid-state laser is a generic name of lasers using a solid-state laser medium.

In addition, for example, Japanese Patent Application Laid-Open No. 8-334803 and corresponding United States Patent No. 5,838,709 proposed an array laser. The array laser is formed to include a plurality of laser elements in a matrix form (for example, a 10×10 matrix). Each of the laser elements is formed to include a laser-beam generating section including a semiconductor laser, and a wavelength conversion section for performing wavelength conversion for light emitted from the laser-beam generating section into ultraviolet light by using a nonlinear optical crystal.

The conventional array laser thus constituted enables an overall-device light output to be a high output while mitigating light outputs of the individual laser elements to be lower. This enables burden onto the individual nonlinear optical crystals to be lessened. On the other hand, however, since the individual laser elements are independent of one another, to apply the lasers to an exposure apparatus, oscillatory spectra of the overall laser elements need to be set identical with one another at the overall width up to a level of 1 pm.

For the above reason, for example, the length of a

resonator of each of the laser elements needs to be adjusted, or a wavelength-selecting device needs to be inserted into the resonator to cause the laser element to autonomously oscillate with the same wavelength in a single longitudinal mode. In this connection, these methods arises other problems. For example, the aforementioned adjustment requires a sensitive arrangement; and in proportion to the increase in the constituent laser elements, the complexity of the configuration needs to be increased to cause the overall devices to oscillate with the same wavelength.

On the other hand, known methods of actively unifying the wavelengths of the plurality of lasers include an injection seed method (for example, see, "Walter Koechner; Solid-state Laser Engineering, 3rd Edition, Springer Series in Optical Science, Vol.1, Springer-Verlag, ISBN 0-387-53756-2, pp.246-249"). According to this method, light from a single laser light source having a narrow spectral linewidth is split into a plurality of laser elements, and the laser beams are used an induction waves to tune the individual laser elements, and in addition, to causes the spectral linewidths to be narrow bandwidths. However, the method has problems in that it requires an optical system for separating the seed light into the individual laser elements and an oscillatory-wavelength tuning control section, thereby increase complexity of the configuration.

In addition, the array laser as described above enables the overall device to be significantly smaller than that with

the conventional excimer laser, it still causes difficulty in packaging so as to reduce the diameter of overall arrayed output beams to several centimeters or smaller. The array laser thus configured has additional problems. For example, each of the arrays requires the wavelength conversion section, thereby increasing the cost. In addition, suppose misalignment has occurred in a part of the laser elements constituting the array, or damage has occurred with the constituent optical elements. In this case, the overall array needs to be once disassembled, the defective part of the laser elements needs to be taken out for repair, and the array needs to be reassembled after repair.

In addition, in the exposure apparatus using such a light source, irradiation (ON) and irradiation termination (OFF) for ultraviolet light provided as exposure light need to be iterated to perform serial exposures of individual shot regions of the wafer. In this case, variations in the exposure-light output (the illuminance when continuous light is used, and the pulse energy when pulsed light is used) are preferably minimized even immediately after the irradiation of the exposure light has been started.

In view of the above-described situations, a primary object of the present invention is to provide an exposure apparatus including a laser device which enables the exposure apparatus to be miniaturized and which has high maintainability.

In addition, a secondary object of the present invention

is to provide an exposure apparatus including a laser device from which a desired output can be obtained even immediately after irradiation (ON) of laser light to the outside has been started.

A third object of the present invention is to provide an exposure apparatus including a laser device which enables the oscillatory frequency to be increased, and enables the spatial coherence to be reduced, as well as enabling the overall oscillatory spectral linewidth to be narrowed with a simple configuration.

Additional object of the present invention is to provide an exposing method and a device-manufacturing method using the aforementioned exposure apparatus, and a manufacturing method of the aforementioned exposure apparatus.

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Disclosure of the Invention

A first exposure apparatus of the present invention illuminates a pattern of a first object (163) with ultraviolet light from a laser device and exposes a second object (166) with the ultraviolet light which has passed through the first object. The laser device includes a laser light generation section (11) which generates single wavelength laser light in a wavelength range of from an infrared region to a visible region, an optical modulating section (12) which modulates the laser light generated by the laser light generation section, an optical amplification section (18-1 to 18-n) including an optical fiber amplifier (22, 25) which amplifies

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the laser light generated by the optical modulating section, and a wavelength conversion section (20) which performs wavelength conversion of the laser light amplified by the optical amplification section into ultraviolet light by using a nonlinear optical crystal (502 to 504). The optical modulating section performs pulse modulation of the laser light from the laser light generation section, and feeds the modulated laser light to the optical amplification section in a period in which the ultraviolet light is output, and the optical modulating section feeds light of an amplifiable wavelength zone to the optical amplification section in a range substantially not influencing an output of the ultraviolet light even in a period in which the ultraviolet light is not output.

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A second exposure apparatus of the present invention illuminates a first object (163) with ultraviolet light from a laser device and exposes a second object (166) with the ultraviolet light which has passed through the first object. The laser device includes a laser light generation section (11) which generates single wavelength laser light, an optical amplification section (18-1 to 18-n) including an optical fiber amplifier which amplifies the laser light, and a wavelength conversion section (20) which performs wavelength conversion of the amplified laser light. The second exposure apparatus is provided with a light feed section (12) which feeds light to the optical amplification section in a condition different from that in a period in which the

ultraviolet light is output even in a period in which the ultraviolet light is not output.

The exposure apparatuses of the above-described aspects of the present invention allow use of the light source which is small and which has a narrow oscillatory spectrum such as, for example, a distributed feed back (DFB) semiconductor laser controlled in an oscillation wavelength or a fiber laser, as the laser light generation section of the laser device. High-output single wavelength ultraviolet light which has a narrow spectral width can be obtained in the following manner. Single wavelength laser light from the laser light generation section is, for example, subjected to pulse modulation at a high frequency enabling a sufficiently high amplification gain to be obtained by an optical fiber amplifier in the optical modulating section (or a light feed section). Then, laser light after the pulse modulation is amplified by the optical fiber amplifier; and thereafter, the laser light is converted into ultraviolet light through the nonlinear optical crystal, resulting in obtaining ultraviolet light of high output and having a narrow spectrum width of a single wavelength. As such, the present invention enables the provision of the exposure apparatus including the laser device which is small and which has high maintainability.

In this case, for example, one of the following amplifiers can be used for the optical fiber amplifier: an erbium(Er)-doped fiber amplifier(EDFA), a ytterbium(Yb)-doped fiber amplifier(YDFA), a praseodymium(Pr)-doped fiber

amplifier(PDFA), and a thulium(Tm)-doped fiber amplifier (TDFA). However, in order to switch the finally obtained ultraviolet light from irradiation termination (OFF) to irradiation (ON), when a pulse train that has been output from the optical modulating section is simply switched from "OFF" to "ON", optical energy stored in the optical fiber amplifier is momentarily output. This causes an "optical surge" that is a phenomenon in which pulsed light that has been output from the optical fiber amplifier immediately after "ON" is increased greater than the pulse train amplified in a steady state. In association with the above, also the output of the ultraviolet light converted in wavelength varies with respect to a desired value.

To reduce the influence of such an optical surge, light of an amplifiable wavelength zone is fed, even in the "OFF" period, to the optical amplification section in a range substantially not influencing the output of the ultraviolet light. Thereby, the output of the ultraviolet light is stabilized.

A first method is provided for feeding the light of an amplifiable wavelength zone to the optical amplification section in a range substantially not influencing the output of ultraviolet light. In the first method, a pulse train having a desired intensity is output to the optical amplification section with a desired timing during the "ON" period (period in which ultraviolet light is output), and one of continuous light and a pulse train is output in the "OFF"

period (period in which ultraviolet light is not output), in which the continuous light has an intensity that is substantially constant at a low peak level, and the pulse train has a near-100% ratio (duty ratio) of high level "1" with respect to one cycle at a low peak level. In addition, preferably, the peak level of the light to be fed to the optical amplification section in the "OFF" period is equal to or smaller than 1/10 of the peak level of the light fed to the optical amplification section in the "ON" period, thereby making an average level of the light output from the optical amplification section in the "ON" period to be substantially the same as an average level of the light output from the optical amplification section in the "OFF" period.

In this case, the conversion efficiency in the wavelength conversion section is proportional to the square of a peak intensity of input light for second-order harmonic generation, and the conversion efficiency is proportional to the product of peak intensities of two input lights for sum frequency generation. For ordinary exposure-apparatus-dedicated ultraviolet light generation, wavelength conversion is performed for, for example, eighth-order harmonic wave and tenth-order harmonic wave generation. The output intensity of ultraviolet light after the last-stage wavelength conversion is therefore proportional to a range of from the eighth power to the tenth power of the intensity of incident light (fundamental wave), and the efficiency in conversion of the output of the optical amplification section

in the "OFF" state to ultraviolet light is substantially zero, and the output of the ultraviolet light becomes substantially zero. Thus, according to the present method, the optical surge influence is reduced, and a state can be implemented in which the output intensity of the ultraviolet light reaches a desired value in the "ON" period, and substantially becomes zero in the "OFF" period.

The intensity of the output from the optical modulating section can be controlled even more accurately by use of an output-light-amount control mechanism.

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A second method is arranged such that, in addition to the laser light generation section (11) (reference light source), an auxiliary light source (51) is provided which generates auxiliary light (whose wavelength hereinbelow will be represented by λ_2) having a wavelength different from that of the laser light (whose wavelength hereinbelow will be represented by λ_1) generated by the laser light generation section, and the auxiliary light is fed to the optical amplification section in the "OFF" period. In this case, the wavelength λ_2 of the auxiliary light is preferably a wavelength which is out of a tolerated wavelength range in which wavelength conversion is possible in the wavelength conversion section, and is preferably a wavelength which is within a gain range of the optical fiber amplifier. Thereby, the optical surge of the optical fiber amplifier can be mitigated without influencing ultraviolet light that is to be finally output.

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The WDM (wavelength division multiplexing) member (52) for combining the auxiliary light with the laser light may be disposed in one of an input portion of the modulator (12) and an output portion thereof. In a configuration where the WDM member is disposed in the input portion of the modulator, the laser light generation section as the reference light source is switched with the same phase as that of the ultraviolet light that is finally output. That is, the laser light generation section is switched "ON" in a period in which the ultraviolet light is in the state of "ON" and the laser light generation section is switched "OFF" in a period in which the ultraviolet light is in the state of "OFF". In addition, switching of the auxiliary light is performed with the opposite phase to the ultraviolet light; that is, switching is performed with a timing in which the auxiliary light source is switched "OFF" when the ultraviolet light is in the "ON" state and the auxiliary light source is switched "ON" when the ultraviolet light is in the "OFF" state. Moreover, the modulator is capable of regularly performing pulse output regardless of the "ON/OFF" state of the ultraviolet light. Furthermore, in the "ON" period of the ultraviolet light, the modulator is capable of performing pulse output, and in the "OFF" period of the ultraviolet light, the modulator is capable of performing output of a constant level of a low peak level or performing pulse output of a high duty ratio. Among the above control patterns is preferably selected a control pattern in which only the light having the wavelength λ_2 is

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output to each of the optical amplification section in the "OFF" state of the ultraviolet light. In a configuration where the WDM member (52) is disposed in the output portion of the modulator (12), light of a low peak level may preferably be fed from the auxiliary light source in the "OFF" state of the ultraviolet light.

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A third method is preferably arranged such that, in addition to the laser light generation section (11) (reference light source), an auxiliary light source (54) is provided which generates auxiliary light of a polarized state different from that of the laser light generated by the laser light generation section and the auxiliary light is fed to the optical amplification section in the "OFF" period. In this case, the polarized state of the laser light from the laser light generation section is preferably a state (for example, linear polarization along a predetermined direction) in which the efficiency of conversion into the ultraviolet light in the wavelength conversion section is maximized. The polarization state of the auxiliary light is preferably a state (such as a state of polarized light of which the polarization direction is perpendicular) in which the efficiency of conversion into the ultraviolet light in the wavelength conversion section is minimized. Thereby, in the "OFF" state of the ultraviolet light, the auxiliary light is fed to the optical fiber amplifier, and the optical surge that can occur thereafter is thereby mitigated. In addition, the conversion efficiency in the wavelength conversion section

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is substantially zero, and the ultraviolet light output intensity substantially becomes zero.

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Similar to the above-described second method, also in the present method, a polarized-wave combining member (55) for combining the auxiliary light with the laser light may be disposed in one of an input portion of the modulator (12) and an output portion thereof. Also control patterns for switching timings for the auxiliary light may be similar to those in the second method. Among the control patterns is preferably selected a control pattern in which only the auxiliary light is fed to the optical amplification section in the "OFF" state of the ultraviolet light.

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Preferably, the laser device of the each of the above-described exposure apparatuses is configured to further include an optical splitter section (14 and 16-1 to 16-m) which splits the laser light generated by the laser light generation section into a plurality of laser light beams, and in this configuration, optical amplification section (18-1 to 18-n) is independently provided for each of the plurality of split laser light beams, and the wavelength conversion section collects fluxes of laser light beams output from the plurality of optical amplification sections and performs wavelength conversion thereof. Thus, the laser light split by the optical splitters are sequentially imparted with predetermined differences in optical path lengths and therefore, the spatial coherence of the laser light finally bundled can be reduced. Moreover, since each of the laser

light beams is generated by the common laser light generation section, the spectral linewidth of the finally obtained ultraviolet light is narrow.

Further, the laser light can be modulated by a light modulation section at a high frequency of, for example, about 100 kHz. Furthermore, each of the pulsed light beams is an aggregate of, for example, 100 delayed pulses of light. As such, in comparison to a case where an excimer laser light (having a wavelength of several kHz) is used, the pulse energy can be reduced to about 1/1000 to 1/10000 to obtain the same illuminance. Therefore, when the above-described laser device is used as an exposure light source, transmittance variations due to, for example, compaction, can substantially be eliminated, and stable and high-accuracy exposure can be implemented.

Concerning the configuration of the wavelength conversion section of the present invention, ultraviolet light formed of a harmonic wave having a frequency of an arbitrary integer multiple (a wavelength of an integer division of 1) with respect to that of the fundamental wave can be easily output through combination of second-order harmonic generation (SHG) by a plurality of nonlinear optical crystals and sum frequency generation (SFG).

For example, ultraviolet light substantially having the same wavelength of 193 to 194 nm as that of an ArF excimer laser can be obtained in a configuration in which a laser light whose wavelength is limited to 1.5 μm, particularly to a range

of from 1.544 to 1.552 μm is irradiated from the laser light generation section, and the eighth-order harmonic wave of the fundamental wave thereof is generated in the wavelength conversion section. Moreover, ultraviolet light substantially having the same wavelength of 157 to 158 nm as that of an F_2 laser can be obtained in a configuration in which laser light whose wavelength is limited to near 1.5 μm, particularly to a range of from 1.57 to 1.58 μm is irradiated from the laser light generation section, and the tenth-order harmonic wave of the fundamental wave thereof is generated in the wavelength conversion section.

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The exposure apparatus of the present invention further includes an illumination system (162) which irradiates a mask (163) with ultraviolet light from the laser device, and a projection optical system (165) which projects an image of a pattern of the mask onto a substrate (166), wherein the substrate is exposed with the ultraviolet light which has passed through the pattern of the mask. With the laser device of the present invention being used, the exposure apparatus can be miniaturized overall, and the maintainability thereof is increased.

In addition, in a first exposure method of the present invention, the ultraviolet light from the laser device is used as alignment light for an exposure apparatus of, for example, a TTR (through the reticle) method type, of the exposure apparatus. The alignment light can be formed to substantially be continuous light, thereby facilitating the

alignment.

A second exposing method of the present invention is a method of illuminating a first object with ultraviolet light from a laser device and exposing a second object with the ultraviolet light which has passed through the pattern of the first object, wherein single wavelength laser light is amplified by an optical fiber amplifier, and the laser light thus amplified is converted in wavelength into ultraviolet light, and light is fed to the optical fiber amplifier in a condition different from that in a period in which the ultraviolet light is output even in a period in which the ultraviolet light is not output. According to this exposure method, similar to the exposure apparatus of the present invention, the laser device can be configured to be small and to have a high maintainability, and a desired output can be obtained even immediately after irradiation (ON) toward outside has been started.

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Next, an exposure apparatus manufacturing method of the present invention is a method of manufacturing an exposure apparatus which illuminates a pattern of a first object (163) with ultraviolet light from a laser device and which exposes a second object (166) with the ultraviolet light which has passed through the pattern of the first object, wherein the laser device is configured by disposing, with a predetermined relationship, a laser light generation section (11) which generates single wavelength laser light in a wavelength range of from an infrared region to a visible region, an optical

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modulating section (12) which modulates the laser light generated by the laser light generation section, an optical amplification section (18-1 to 18-n) including an optical fiber amplifier (22 and 25) which amplifies the laser light generated by the optical modulation section, and a wavelength conversion section (20) which performs wavelength conversion of the laser light amplified by the optical amplification section into ultraviolet light by using a nonlinear optical crystal (502 to 504), and wherein the optical modulating section is configured such that the laser light output from the laser light generation section is pulse-modulated and fed to the optical amplification section in a period in which the ultraviolet light is output, and light of an amplifiable wavelength zone is fed to the optical amplification section in a range substantially not influencing output of the ultraviolet light even in a period in which the ultraviolet light is not output.

Furthermore, a device manufacturing method of the present invention includes a step of transferring a mask pattern onto a substrate by using the exposure apparatus of the present invention.

Brief Description of the Figures in the Drawings

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Fig. 1 is a diagram showing an ultraviolet light generator of a first embodiment of the present invention.

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Fig. 2 is a diagram showing a configuration example of optical amplifier units 18-1 to 18-n shown in Fig. 1.

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In Fig. 3, Fig. 3(a) is a diagram showing a first configuration example of a wavelength conversion section 20 shown in Fig. 1, and Fig. 3(b) is a diagram showing a second configuration example of the wavelength conversion section 20.

In Fig. 4, Fig. 4(a) is a diagram showing a third configuration example of a wavelength conversion section 20, and Fig. 4(b) is a diagram showing a fourth configuration example of the wavelength conversion section 20.

Fig. 5 is an explanatory view of a case where an optical surge occurs in the optical fiber amplifier shown in Fig. 1.

Fig. 6 is a diagram showing a state of a laser beam that is to be output from an optical modulating device 12 and a state of a finally output laser beam LB5 in an ultraviolet region according to a first embodiment of the present invention.

Fig. 7 is a configuration view of an optical modulating section according to a second embodiment of the present invention.

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Fig. 8 is a timing chart showing an example of a driving method for individual laser beams and the optical modulating device 12 according to the second embodiment.

Fig. 9 is a timing chart showing another example of a driving method for individual laser beams and the optical modulating device 12 according to the second embodiment.

Fig. 10 is a configuration view of an optical modulating section according to a third embodiment of the present

invention.

Fig. 11 is a configuration view of a modified example of the second embodiment.

Fig. 12 is a configuration view of a modified example of the third embodiment.

Fig. 13 is a configuration view showing an example of an exposure apparatus employing an ultraviolet light generator of the above-mentioned embodiments.

Best Mode for Carrying out the Invention

Hereinbelow, a preferred first embodiment according to the present invention will be described with reference to the accompanying drawings. The present embodiment represents a configuration in which the present invention is applied to an ultraviolet light generator that can be used as an ultraviolet-region exposure light source of a projection exposure apparatus such as a stepper method or a step-and-scan method or as a light source for alignment and various tests.

Fig. 1(a) shows an ultraviolet light generator according to the present embodiment. Referring to Fig. 1(a), a single wavelength oscillatory laser 11, which is provided as a laser light generation section, generates a laser beam LB1 that is formed of, for example, a continuous wave (CW) having a narrow spectral width and that has a wavelength of 1.544 μm. The laser beam LB1 is incident on an optical modulating device 12, which is provided as an optical modulator, via an isolator IS1 provided for blocking reverse

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light. The laser beam LB1 is converted therein into a laser beam LB2 (pulsed beam), and the laser beam LB2 is then incident on an optical splitting amplifier section 4.

The laser beam LB2 incident on the optical division amplifier section 4 passes through an optical fiber amplifier 13 provided as a front-stage optical amplification section, passes through the optical fiber amplifier 13, and is amplified therethrough. The amplified beam is then incident on a splitter 14 of a planar waveguide type provided as a first optical splitting device via an isolator IS2, and is then split into m laser beams each having the same optical intensity. The letter m represents integer "2" or a greater integer. In the present embodiment, m = 4. For the optical fiber amplifier 13, the apparatus uses an erbium-doped fiber amplifier (EDFA) to amplify light having the same wavelength zone (which is near 1.544 μm in the present embodiment) as that of the laser beam LB1, which generated by the single wavelength oscillatory laser 11. An excitation beam having a wavelength of 980 nm is fed into the optical fiber amplifier 13 via a coupling-dedicated wavelength division multiplexing device (not shown). An excitation beam having a wavelength of (980±10) nm or (1480±30) nm can be used for the erbium-doped fiber amplifier (EDFA). However, to prevent the increase in wavelength according to nonlinear effects, the 980 nm laser beam is preferably used as excitation beam to thereby reduce the fiber length. In comparison to the case where the light in the 1480 nm band, using the 980 nm excitation beam is more

preferable also in that noise occurring in the optical fiber amplifier 13 because of amplified spontaneous emission (ASE) can be reduced. The above is the same for a rear-stage optical fiber amplifier.

A (970±10) nm beam may be used as the excitation beam for either an ytterbium(Yb)-doped fiber or an erbium/ytterbium-codoped fiber.

The m laser beams that have been output from the splitter 14 are incident on planar-waveguide-type splitters 16-1, 16-2, …, and 16-m individually provided as second optical splitting devices via respective optical fibers 15-1, 15-2, …, and 15-m each having a different length. Thereby, the m laser beams are each split into n laser beams each having substantially the same optical intensity. The letter n represents "2" or a greater integer; and n = 32 in the present embodiment. The first optical splitting device (14) and the second optical splitting devices (16-1 to 16-m) correspond to optical splitters of the present embodiment according to the present invention. Consequently, the laser beam LB1 emitted from the single wavelength oscillatory laser 11 is split overall into n·m laser beams (that is, 128 laser beams in the present embodiment).

N laser beams LB3 output from the splitter 16-1 are incident on optical amplifier units 18-1, 18-2, …, and 18-n, individually provided as rear-stage optical amplification sections, via respective optical fibers 17-1, 17-2, …, and 17-n each having a different length; and the incident beams

are amplified therethrough. The optical amplifier units 18-1 to 18-n each amplify a laser beam having the same wavelength zone (near 1.544 μm in the present embodiment) as that of the laser beam LB1 generated by the single wavelength oscillatory laser 11. Similar to the above, n laser beams output from the other splitter 16-2 to 16-m are incident on optical amplifier units 18-1 to 18-n, individually provided as the rear-stage optical amplification sections, via respective optical fibers 17-1 to 17-n each having a different length; and the incident beams are amplified therethrough.

The laser beams amplified by the m-group optical amplifier units 18-1 to 18-n propagate through extended portions of output terminals of optical fibers (described below) doped with a predetermined matter in the respective optical amplifier units 18-1 to 18-n. The aforementioned extended portions form a fiber bundle 19. The lengths of the m-group n optical fibers forming the fiber bundle 19 are identical to one another. However, the configuration may be such that the fiber bundle 19 is formed bundling, and the laser beams amplified by the optical amplifier units 18-1 to 18-n are transferred to the corresponding optical fibers. Thus, the optical splitting amplifier unit 4 is configured to include the members provided between the optical fiber amplifier 13 and the fiber bundle 19. The configuration of the optical splitting amplifier section 4 is not limited to that shown in Fig. 1. For example, a time division multiplexer may be used as an optical splitter.

Laser beams LB4 having been output from the fiber bundle 19 are incident on a wavelength conversion section 20 including a nonlinear optical device, and is converted thereby into laser beams LB5 each formed of ultraviolet light. The laser beams LB5 are output to the outside as alignment light or testing light. As described above, the m-group optical amplifier units 18-1 to 18-n are provided to individually correspond to the optical amplification sections of the present invention. However, a case may be in which the optical fibers in the fiber bundle 19 are included in the optical amplification sections.

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~~Moreover, as shown in Fig. 1(b), output terminals 19a of the fiber bundle 19 are bundled such that the $m \times n$ optical fibers (128 optical fibers in the present embodiment) tightly contacts one another, and the outer shape thereof is circular in a cross-sectional view. In a practical configuration, however, the outer shape of the output terminals 19a and the number of optical fibers are determined according to, for example, the rear-stage configuration of the wavelength conversion section 20 and use conditions of the ultraviolet light generator of the present embodiment. The clad diameter of each of the optical fibers constituting the fiber bundle 19 is about 125 μm. Accordingly, when 128 optical fibers are bundled circular, a diameter d1 of each of the output terminals 19a can be set to about 2 mm or smaller.~~

In addition, the number of the optical fibers to constitute the optical fiber bundle 19 may arbitrarily be

determined. For example, the number of the optical fibers is determined according to a required value of the illuminance on the wafer; the transmittance of an illumination system and the transmittance of a projection system; the conversion efficiency of the wavelength conversion section 20; and outputs (powers) of the individual optical fibers. However, the plurality of optical fibers may be used without bundling in the form of an optical fiber bundle.

The wavelength conversion section 20 according to the present embodiment converts the incident laser beam LB4 to a laser beam LB5 formed of either an eighth-order harmonic wave (wavelength: 1/8) or a tenth-order harmonic wave (wavelength: 1/10). The wavelength of the laser beam LB1 output from the single wavelength oscillatory laser 11 is 1.544 μm. Accordingly, the wavelength of the eighth-order harmonic wave is 193 nm, which is the same as that of the ArF excimer laser; and the wavelength of the tenth-order harmonic wave is 154 nm, which is substantially the same as the wavelength (157 nm) of the F_2 laser (fluorine laser). Suppose a case occurs in which the wavelength of the laser beam LB5 needs to be approximated closer to the wavelength of the F_2 laser. This case can be achieved such that the wavelength conversion section 20 is controlled to generate a tenth-order harmonic wave, and in addition, the single wavelength oscillatory laser 11 is controlled to generate a laser beam having a wavelength of 1.57 μm.

In practice, ultraviolet light substantially having the

same wavelength (193 to 194 nm) as that of the ArF excimer laser can be obtained in such a way that the oscillation wavelength of the single wavelength oscillatory laser 11 is regulated to be in a range of from 1.544 to 1.552 µm, and is converted to the eighth-order harmonic wave. Similarly, ultraviolet light substantially having the same wavelength (157 to 158 nm) as that of the F_2 laser in such a way that the oscillation wavelength of the single wavelength oscillatory laser 11 is regulated to be in a range of from 1.57 to 1.58 µm, and is converted to the tenth-order harmonic wave. As such, these ultraviolet light generators can be used as inexpensive and easily maintainable light sources in place of the ArF excimer laser source and the F_2 laser source.

Alternative other methods may be employed instead of the method of finally obtaining the ultraviolet light having the wavelength that is close to the wavelength zone of the ArF excimer laser or the F_2 laser. For example, in one of the alternative methods, an optimal exposure-light wavelength (for example, 160 nm, or the like) is determined according to patterning rules furnished for a manufacturing object such as a semiconductor device; and, for example, the oscillation wavelength of the single wavelength oscillatory laser 11 and the magnification of harmonic waves in the wavelength conversion section 20 are thereby determined so that ultraviolet light having a theoretically optimum wavelength can be obtained. That is, the wavelength of the ultraviolet light may be arbitrary; and, for example, the oscillation

wavelength of the single wavelength oscillatory laser 11, and the configuration and the conversion magnification in the wavelength conversion section 20 may be determined according to a required wavelength in a product to which the present laser device is applied.

Sb A18

Hereinbelow, the present embodiment will be described in further detail. Referring to Fig. 1 (a), for the single wavelength oscillatory laser 11 oscillating at a single wavelength, the present embodiment uses, a laser, such as a distributed feedback (DFB) semiconductor laser. The DFB semiconductor laser is characterized by an InGaAsP construction, a 1.544 μm oscillation wavelength, and a 20 mW continuous output (which hereinbelow will be referred to as "CW output"). In addition, the DFB semiconductor laser is configured such that, instead of a Fabry-Pelot resonator, a diffraction grating is formed in a semiconductor laser, in which single longitudinal mode oscillation is performed under any condition. Thus, since the DFB semiconductor laser performs the single longitudinal mode oscillation, the oscillation spectral linewidth can be controlled to be 0.01 pm or less. Alternatively, for the single wavelength oscillatory laser 11, the present embodiment may be configured using a light source such as an erbium(Er)-doped fiber laser capable of generating a laser beam having a wavelength region similar to the above and a narrowed bandwidth.

In addition, the output wavelength of the ultraviolet light generator of the present embodiment is preferably fixed

to a specific wavelength depending on the usage. As such, the present example includes an oscillation wavelength controller provided to control the oscillation wavelength of the single wavelength oscillatory laser 11, provided as a master oscillator, to be a predetermined wavelength. As in the present embodiment, in the configuration using the DFB semiconductor laser for the single wavelength oscillatory laser 11, the oscillation wavelength can be controlled according to a method of controlling the temperature of the DFB semiconductor laser. This method enables, for example, the oscillation wavelength to be more stably controlled to be a predetermined wavelength, and the output wavelength to be finely tuned.

Ordinarily, a component such as the DFB semiconductor laser is provided over a heatsink, and the components are stored in a package. In the present example, a temperature regulator section 5 (which is formed of, for example, a heating device such as a heater, a heat absorbing device such as a Peltier device, a temperature detecting device, and a thermistor) is fixed to a heatsink attached to the single wavelength oscillatory laser 11 (such as the DFB semiconductor laser). In this configuration, operation of the temperature regulator section 5 is controlled by a control section 1 comprising a computer, and the temperatures of the heatsink and the single wavelength oscillatory laser 11 are thereby controlled with a high accuracy. For example, the temperature in the DFB semiconductor laser can be controlled

in units of 0.001°C. Moreover, the control section 1 performs high-accuracy control for power (driving current in the DFB semiconductor laser) for driving the single wavelength oscillatory laser 11 via a driver 2.

The oscillation wavelength of the DFB semiconductor laser has a temperature dependency of about a 0.1 nm/°C. When the temperature of the DFB semiconductor laser is changed by, for example, 1°C, the wavelength is changed by 0.1 nm in the fundamental wave (wavelength: 1544 nm). Accordingly, in the eighth-order harmonic wave (193 nm), the wavelength thereof is changed by 0.1 nm; and in the tenth-order harmonic wave (157 nm), the wavelength thereof is changed by 0.01 nm. When the laser beam LB5 is used for the exposure apparatus, compensation needs to be performed for, for example, errors that can occur according to differences in atmosphere of environments where the exposure apparatus is placed or errors that can occur because of variations in imaging properties. As such, preferably, the laser beam LB5 can preferably be varied by about ±20 pm with respect to the central wavelength. This can be implemented by changing the temperature of the DFB semiconductor laser by about ±1.6°C for the eighth-order harmonic wave and by ±2°C for the tenth-order harmonic wave.

For a monitor wavelength used in feedback control when controlling the above-described oscillation wavelength to be a predetermined wavelength, a wavelength that provides sensitivity necessary for desired wavelength control and that has high monitorablility may be selected from post-

wavelength-conversion harmonic-wave outputs (such as a second-order harmonic wave, a third-order harmonic wave, and a fourth-order harmonic wave) in the wavelength conversion section 20 (described below). In an event a 1.51-to-1.59 μm DFB semiconductor laser is used for the single wavelength oscillatory laser 11, the third-order harmonic wave of the oscillation laser beam has a wavelength in a range of from 503 nm to 530 nm. This wavelength band corresponds to a wavelength zone wherein iodine-molecule absorption lines are present at a high density. As such, even higher-accuracy wavelength control can be implemented in such a way that an appropriate iodine-molecule absorption line is selected and is locked to the wavelength thereof. The present embodiment is arranged such that a predetermined harmonic wave (preferably, the third-order harmonic wave) in the wavelength conversion section 20 is compared with the selected appropriate iodine-molecule absorption line (reference wavelength), and the differential amount of the wavelength is fed back to the control section 1. Then, based on the feedback, the control section 1 controls the temperature of the single wavelength oscillatory laser 11 via the temperature regulator section 5 to cause the differential amount to become a predetermined value. In this case, the control section 1 may be arranged such that the oscillation wavelength of the single wavelength oscillatory laser 11 is positively controlled to vary, and the output wavelength thereof can be tuned.

For example, in an exposure apparatus exposure light source to which the ultraviolet light generator of the present embodiment is applied, the former method, described above, enables the prevention of aberration from occurring with a projection optical system because of wavelength variations. Consequently, the method avoids variations in imaging properties (optical properties such as image quality) to occur during pattern transfer. The latter method, described above, enables compensation for variations in image properties (such as aberrations) of the projection optical system. The variations can occur because of, for example, an elevational difference and an atmospheric difference between a manufacturing site, in which the exposure apparatus is assembled and tuned, and a placement site (delivery site) of the exposure apparatus. The variations can also occur because of a difference in environments (such as inter-clean-room atmospheres). This enables reduction in time required for installation of the exposure apparatus in the delivery site. Moreover, the latter method enables compensation for variations of various types that occur during operation of the exposure apparatus. The variations include those in aberrations with an illumination optical system, in projection magnification, and focal position. These variations can occur in association with changes in reticle illumination conditions (specifically, illuminant-energy distributions of exposure illumination light on a pupillary surface of an illumination optical system) according to

irradiation of exposure illumination light, atmospheric variations, and illumination optical systems. As such, the latter method enables a pattern image to be transferred on a substrate always in the best imaging condition.

Sub a19

The laser beam LB1, formed of continuous light output from the single wavelength oscillatory laser 11, is converted into the laser beam LB2, formed of a pulsed beam, by use of the optical modulating device 12. The optical modulating device 12 is formed of, for example, an electrooptical modulating device or an acousto-optical modulating device. The optical modulating device 12 is driven by the control section 1 through the driver 3. The optical modulating device 12 can be considered to be a part of the light supply portion. As shown in Figs. 6(a) and 6(b), the laser beam LB2 that has been output from the optical modulating device 12 of the present example is a pulse train of a peak level LB in a period in which the laser beam LB5 in the form of ultraviolet light is output, that is, in the "ON" period. The laser beam LB2 is continuous light of a level LA in a period in which the laser beam LB5 in the form of ultraviolet light is not output, that is, in the "OFF" period. In Figs. 6(a) and 6(b) (also in Fig. 5), the horizontal axis represents time "t", and the vertical axis represents the laser-beam output (energy per unit time).

Sub a20

Referring to Fig. 6, an average level (average value obtained through integration) of the laser beam LB2 during the period in which the ultraviolet light is "ON" is set to

Sub A20

be substantially the same as an average level (= LA) of the laser beam LB2 during the period in which the ultraviolet light is "OFF". In this case, duty ratio (ratio (%) of a high level "1" period to the pulse cycle) of the laser beam LB2 in the period in which the ultraviolet light is "ON" is set to be 1/10 or lower, and is ordinarily set to be about 1/10000. Therefore, the level LA is 1/10 or lower with respect to the peak level LB, and is ordinarily about 1/10000 or lower. Thus, the level of the laser beam LB2 is maintained to be at the predetermined level LA even in the period in which the ultraviolet light is "OFF". This prevents the output power of the ultraviolet light (laser beam LB5) from increasing according to increase in gains because of optical surges in the rear-stage optical fiber amplifier 13 and the optical fiber amplifiers (the optical fiber amplifiers 22 and 25 shown in Fig. 2) in the optical amplifier units 18-1 to 18-n when the ultraviolet light is switched "ON". On the other hand, however, as shown in Fig. 5(a), when the output power of the laser beam LB2 is set to 0, as shown in Fig. 5(b), an optical surge occurs of the rear-stage optical fiber amplifier in a period TS immediately after the ultraviolet light is switched "ON". This increases the peak level of the pulse train of the ultraviolet light (laser beam LB5), causing the output power of the ultraviolet light to deviate from the desired value.

Sub A21

The wavelength conversion section 20 shown in Fig. 1 converts the input laser beam LB4 into the laser beam LB5 in

the form of ultraviolet light through at least three stages of nonlinear optical crystals (which will be described below in detail). In this case, in each of the nonlinear optical crystals, wavelength conversion is performed substantially in proportion either to the square of the peak level of incident light or to the product of the peak levels of the two incident lights. Consequently, the output power of the laser beam LB5 that is to be output from the wavelength conversion section 20 is proportional to a coefficient which is equal to or higher than the eighth power (= the power of 2^3) of the peak level of the incident laser beam LB4. Therefore, in Fig. 6, with respect to the peak level LB of the laser beam LB2 in the period in which the ultraviolet light is "ON", the level LA of the laser beam LB2 in the period in which the ultraviolet light is "OFF" is 1/10 or lower, and is ordinarily about 1/10000 or lower. As such, since the light of the level LA is hardly converted into ultraviolet light (laser beam LB2), the level of the laser beam LB5 substantially completely becomes zero in the period in which the ultraviolet light is "OFF". Consequently, the output power of the ultraviolet light (laser beam LB5) reaches the desired value even in either the "ON" or "OFF" period.

Hereinbelow, a description will be made with reference to an example of the present example configuration in which the optical modulating device 12 performs the modulation into a pulsed beam characterized by a pulsewidth of 1 ns and a repetition frequency of 100 kHz (pulse cycle: 10 μs). As a

result of the optical modulation, the peak output power LB of the pulsed beam produced from the optical modulating device 12 in the period in which the ultraviolet light is "ON" becomes 20 mW, and the average output power thereof becomes 2 µW. In this case, the level LA of the continuous light output from the optical modulating device 12 in the period in which the ultraviolet light is "OFF" is 2 µW, that is, LB/10000. In the example case, no loss is assumed to occur because of insertion of the optical modulating device 12. However, a loss of the insertion occurs in practice. For example, with a loss of -3 dB, the value of the peak output is thereby reduced to 10 mW, and the value of the average output is thereby reduced to 1 µW.

When using an electrooptical modulating device for the optical modulating device 12, the electrooptical modulating device is preferably of a type (such as a two-electrode-type modulator) that has an electrode structure subjected to chirp compensation. The aforementioned modulator is preferably used to reduce the wavelength expansion of a semiconductor-laser output, which is caused by chirp occurring according to a timewise variation in the refractive index. In addition, in the optical fiber amplifiers in the optical amplifier units 18-1 to 18-n, the amplification factor can be can be prevented from being reduced because of influence of ASE (amplified spontaneous emission) noise. The above prevention can be achieved by setting the repetition frequency to a level of 100 kHz or higher. Moreover, suppose the

illuminance of ultraviolet to be finally output may be the same level as that of a conventional excimer laser beam (of which the pulse frequency is a level of several kHz). In this case, as in the present example, the pulse frequency is increased, and individual pulses are, for example, a 128 delayed pulse. Thereby, the per-pulse energy can be reduced to a level of 1/1000 to 1/10000 to reduce variations, which can occur by compaction and the like, in refractive index of an optical member (such as a lens). For this reason, the modulator is preferably configured as described above.

Furthermore, a semiconductor laser or the like can be caused to generate output light through pulse oscillation by controlling the current of the laser. As such, the present example preferably uses the current (power) control for the single wavelength oscillatory laser 11 (such as the DFB semiconductor laser) and the optical modulating device 12 in association. The power control for the single wavelength oscillatory laser 11 is performed to oscillate a pulsed beam having a pulsewidth of, for example, a level of 10 to 20 ns. Concurrently, the optical modulating device 12 is used to take out a part of the pulsed beam. Thus, the present example performs modulation into a pulsed beam having a pulsewidth of 1 ns. In addition, a case can occur in which even when only the optical modulating device 12 is used to cause the pulsed beam to be in the "OFF" state, the extinction ratio thereof is still insufficient. In this case, preferably, the power control for the single wavelength oscillatory laser 11

is concurrently employed.

Sub a22

In Fig. 1(a), the pulsed beam output thus obtained is then coupled to the erbium-doped optical fiber amplifier 13 on the initial stage, and 35 dB (3162 times) amplification is performed thereby. At this stage, the pulsed beam is amplified to have a peak output power of about 63 W and an average output power of about 6.3 mW. In the above-described configuration, a multistaged optical fiber amplifier may be used to replace the optical fiber amplifier 13.

The output of the initial-stage optical fiber amplifier 13 is first parallely split using the splitter 14 into four outputs for channels 0 to 3 (in the present example, m = 4). Outputs of the respective channels 0 to 3 are then couple to the optical fibers 15-1 to 15-4 having the lengths different from one another. Thereby, delay times corresponding to the optical fiber lengths are allocated for the outputs of the optical fibers 15-1 to 15-4. For example, in the present embodiment, the propagation rate of light in each of the optical fibers is assumed to be 2×10^8 m/s. The optical fibers 15-1 to 15-4 respectively having lengths of 0.1 m, 19.3 m, 38.5 m, and 57.7m are coupled to the channels 0, 1, 2, and 3, respectively. In this case, the delay of light between the adjacent channels at an exit terminal of each of the optical fibers is 96 ns. For the convenience of description, the optical fibers 15-1 to 15-4 thus used for delaying the light are each called a "delay fiber".

Subsequently, the outputs of the four delay fibers are

further parallely split by the splitters 16-1 to 16-4 into n outputs (in the present example, n = 32) (by each of the splitters for channels 0 to 31). That is, the outputs are split into the total of 4 × 32 (= 128) channels. Then, the respective optical fibers 17-1 to 17-32 (delay fibers) each having a different length are coupled to output terminals of the channels 0 to 31 to allocate a 3-ns delay time between the adjacent channels. That is, a 93-ns delay time is allocated for the channel 31. On the other hand, the 96-ns delay time is allocated for the first to fourth splitters 16-1 to 16-4 at the time of input. Consequently, at output terminals of the total 128 channels provided overall, the pulsed beam having the 3-ns delay time between the adjacent channels can be obtained.

As a result of the above, the spatial coherence of the laser beam LB4, which is to be output from the fiber bundle 19, is reduced on the order of 1/128, in comparison to a case where a cross-sectional shape of the laser beam LB1 to simply be output from the single wavelength oscillatory laser 11 is enlarged. As such, the present example exhibits an advantage in that the amount of speckles occurable when the finally obtainable laser beam LB5 is used as exposure light is very small.

As described above, according to the splitting process and the delay-time allocation, the present example enables the pulsed beams having the 3-ns delay time between the adjacent channels to be obtained at the output terminals of

the total 128 channels. The pulsed beam observed at each of the output terminals has the same frequency of 100 kHz (pulse cycle: 10 μs) as that of the pulsed beam modulated by the optical modulating device 12. Accordingly, in view of the overall laser light generation section, repetition takes place at a cycle of 100 kHz such that 128 pulses are generated at 3-ns intervals, and a subsequent pulse train is then generated after an interval of 9.62 μs.

In the present embodiment, description has been made with reference to the example in which the split number is 128, and the relatively short delay fibers are used. As such, a non-emission interval of 9.62 μs occurs between the individual pulse trains. However, the pulse intervals can be completely equalized in such a way that the split numbers m and n are increased, or appropriately longer delay fibers are used, or a combination thereof is employed.

According to the above, it can be viewed that a time division multiplexing means (TDM means) is configured overall by the splitter 14, optical fibers 15-1 to 15-m, splitters 16-1 to 16-m, and m-group optical fibers 17-1 to 17-n of the present example. In the present example, the time division multiplexing means is configured of two stages of the splitters. However, the time division multiplexing means may be configured of three or more stages of splitters; or alternatively, it may be configured only of one stage of splitters while the split number is reduced. Moreover, while the splitters 14 and 16-1 to 16-m are of a planar waveguide

type, the configuration may use splitters of a different type, such as fiver splitters or beam splitters using a partial transmission mirror.

Sub A23

In addition, the present example is capable of tuning the oscillation timing, i.e., a repetition frequency f by controlling the timing of a driving voltage pulse applied to the optical modulating device 12. Moreover, in a case where output variations can occur with the pulsed beam according to a change in the oscillation timing, the arrangement may be made such that the magnitude of the driving voltage pulse, which is to be applied to the optical modulating device 12, is synchronously tuned to compensate for the output variations. In this case, the arrangement may be such that the pulsed-beam output variations are compensated for only through the use of oscillation control of the single wavelength oscillatory laser 11 or through the associated use thereof with the above-described control of the optical modulating device 12. Referring to Fig. 1(a), the laser beams passed through the m-group delay fibers (optical fibers 17-1 to 17-n) are incident on the respective optical amplifier units 18-1 to 18-n, and are amplified thereby. The individual optical amplifier units 18-1 to 18-n of the present example have optical fiber amplifiers. While description given hereinbelow will cover example configurations of an optical amplifier unit that may be used for the optical amplifier unit 18-1, the example configurations may similarly be used for the other optical amplifier units 18-2 to 18-n.

Fig. 2 shows an example of an optical amplifier unit 18. Referring to Fig. 2, the optical amplifier unit 18 shown therein is basically configured to include two stages of optical fiber amplifiers 22 and 25 being coupled. The individual optical fiber amplifiers 22 and 25 are formed of erbium-doped fiber amplifiers (EDFAs). Two end portions of the first-stage optical fiber amplifier 22 are coupled to wavelength division multiplexing devices 21A and 21B (each of which hereinbelow will be referred to as a "WDM device"). The respective WDM devices 21A and 21B feed an excitation beam EL1 and another excitation beam forwardly and backwardly to the optical fiber amplifier 22. The excitation beam EL1 is fed from a semiconductor laser 23A, provided as a laser light source; and the other laser beam is fed from a semiconductor laser 23B, provided as a laser light source. Similarly, two end portions of the second-stage optical fiber amplifier 25 are coupled to coupling-dedicated WDM devices 21C and 21D. The respective WDM devices 21C and 21D forwardly and backwardly feed excitation beams, fed from semiconductor lasers 23C and 23D, to the optical fiber amplifier 25. Thus, each of the optical fiber amplifiers 22 and 25 is of a two-way excitation type.

Each of the optical fiber amplifiers 22 and 25 amplifies light having a wavelength in a range of, for example, from about 1.53 to 1.56 μm, which is inclusive of the wavelength of the incident laser beam LB3 (in the present example, the wavelength thereof is 1.544 μm). A narrow band filter 24A

and an isolator IS3 for blocking reverse light are disposed in a boundary portion between the optical fiber amplifiers 22 and 25, more specifically, between the WDM devices 21B and 21C. For the narrow band filter 24A, either a multilayer film filter or a fiber bragg grating may be used.

Sub A25

~~In the present example, the laser beam LB3 from the optical fiber 17-1 shown in Fig. 1(a) is led via the WDM device 21A to be incident on the optical fiber amplifier 22, and is amplified thereby. Then, the laser beam LB3 amplified by the optical fiber amplifier 22 is incident on the optical fiber amplifier 25 via the WDM device 21B, the narrow band filter 24A, the isolator IS3, and WDM device 21C; and the incident laser beam LB3 is thereby amplified again. Via the WDM device 21D, the amplified laser beam LB3 propagates through one of optical fibers that constitute the fiber bundle 19 shown in Fig. 1(a) (the aforementioned optical fiber may be an extended portion of an output terminal of the optical fiber amplifier 25).~~

The total of amplification gains according to the second-stage optical fiber amplifiers 22 and 25 is 46 dB (39,810 times) as one example. When the total number of channels (m·n pieces) output from the splitters 16-1 to 16-m shown in Fig. 1(b) is 128, and the average output power of each of the channels is about 50 μm, the average output power of all the channels is about 6.4 mW. When a laser beam of each of the channel is amplified at about 46 dB, the average output power of the laser beam output from each of the optical

amplifier units 18-1 to 18-n is about 2 W. When the above is assumed to have been pulsed at a pulsewidth of 1 ns, and a pulse frequency of 100 kHz, the peak output power of each of the laser beams is 20 kW. Also, the average output power of the laser beam Lb4 output from the fiber bundle 19 is about 256 W.

Sub A26

In the present example, coupling losses in the splitters 14 and 16-1 to 16-m shown in Fig. 1(a) are not taken into consideration. However, even when the coupling losses occur, the output powers of the laser beams of the individual channels can be unformed to be the above-described value (for example, the peak output power of 20 kW). This can be achieved by increasing at least one of the amplification gains obtained according to the optical fiber amplifiers 22 and 25 by the amount of the loss. In addition, the value of the output power (output power of the fundamental wave) of the single wavelength oscillatory laser 11 shown in Fig. 1(a) can be controlled larger or smaller than the aforementioned value. This can be achieved by controlling the amplification gains obtained according to the optical fiber amplifiers 22 and 25.

Sub A27

Referring to the example configuration shown in Fig. 2, the narrow band filter 24A removes ASE (amplified spontaneous emission) light occurring in each of the optical fiber amplifier 13 shown in Fig. 1(a) and the amplifying optical fiber 22 shown in Fig. 2, and lets the laser beam (having a wavelength width of 1 pm or less) output from the single wavelength oscillatory laser 11 shown in Fig. 1(a) to

Sub a27

~~transmit. Thereby, the narrow band filter 24A substantially makes the wavelength width of the transmitted beam to be a narrow band. This enables the amplification gain of the laser beam to be prevented from being reduced by the incidence of the ASE light. In this case, the narrow band filter 24A preferably has a transmission wavelength width of about 1 pm. However, since the wavelength width of the ASE light is several tens of nm, the ASE light can be removed not to cause a problem in practice even by using a currently available narrow band filter with a transmission wavelength width of about 100 pm.~~

Sub a28

~~Suppose the output wavelength of the single wavelength oscillatory laser 11 in Fig. 1(a) is positively changed. In this case, while the narrow band filter 24A may be replaced according to the output wavelength. However, preferably, a narrow band filter having a transmission wavelength width (equivalent to a variable range (about ±20 pm, as mentioned above as an example, for an exposure apparatus) is used. Further, the isolator IS3 reduces the influence of reverse light attributed to nonlinear effects of the optical fibers. The optical amplifier unit 18 may be configured by coupling three or more stages of optical fiber amplifiers. Also in this case, the narrow band filter 24A and the isolator IS3 are preferably inserted into the boundary portion between the two adjacent optical fiber amplifiers in the overall configuration.~~

In the present example, since a large number of the output beams of optical amplifier unit 18 are bundled and are

used in the bundled state, the intensities of the individual output beams are preferably homogenized. This can be implemented in, for example, the following manner. A part of the laser beam LB3 output from the WDM device 21D is isolated, the isolated light is photoelectrically converted, and the luminous quantities of laser beams LB3 to be output are thereby monitored. Then, outputs of excitation light sources (semiconductor lasers 23A to 23D) in each of the optical amplifier units 18 are controlled so that the aforementioned luminous quantities are substantially equal to one another in all the optical amplifier units 18.

In the above-described embodiment, the laser light source having an oscillation wavelength of about 1.544 μm is used for the single wavelength oscillatory laser 11. Instead of this laser light source, however, the embodiment may use a laser light source having an oscillation wavelength in a range of from 1.099 to 1.106 μm. For this laser light source, either a DFB semiconductor laser or an ytterbium(Yb)-doped fiber laser may be used. In this case, for the optical fiber amplifier in the rear-stage optical amplification section, the configuration may use an ytterbium(Yb)-doped fiber (YDFA) that performs amplification in a wavelength zone of 990 to 1200 nm including the wavelength of the amplifier section. In this case, ultraviolet light having a wavelength of 157 to 158 nm wave that is substantially the same wavelength of the F_2 laser can be obtained by outputting the seventh-order harmonic wave in the wavelength conversion section 20 shown

b 29

in Fig. 1(b). In practice, ultraviolet light having substantially the same wavelength as that of the F_2 laser can be obtained by controlling the oscillation wavelength to be about 1.1 μm.

Moreover, the arrangement may be made such that the fourth-order harmonic wave of the fundamental wave is output in the wavelength conversion section 20 by controlling the oscillation wavelength in the single wavelength oscillatory laser 11 to be near 990 nm. This enables ultraviolet light having a same wavelength of 248 nm as that of the KrF excimer laser to be obtained.

In the last-stage high-peak-output optical fiber amplifier (for example, the optical fiber amplifier 25 in the optical amplifier unit 18 shown in Fig. 2), according to above-described present embodiment, it is preferable to use a large mode diameter fiber having a fiber mode diameter of, for example, 20 to 30 μm, which is larger than that is ordinarily used (5 to 6 μm), to avoid the increase in the spectral width according to the nonlinear effects in the fiber.

Moreover, a double clad fiber having a double clad structure may be used in place of the large mode diameter fiber to obtain a high level output in the last-stage optical fiber amplifier (for example, optical fiber amplifier 25 shown in Fig. 2). In this optical fiber, a core portion is doped with ion that contributes to amplification of laser light, and the amplified laser light propagates through the inside of the

core. An excitation-dedicated semiconductor laser is coupled to the first clad that covers the core. The first clad serves in a multimode and has a large cross section. As such, the high-output excitation-dedicated semiconductor laser beam can easily be transmitted therethrough, a multimode-oscillation semiconductor laser can be efficiently coupled, and hence, the excitation-dedicated light source can efficiently be used. A second clad for forming a waveguide of the first clad is formed on the circumference of the first clad.

A quarts fiber or a silicate-based fiber may be used for the optical fiber amplifier of the above-described embodiment. Alternatively, a fluoride-based fiber, such as a ZBLAN fiber, may be used. With the fluoride-based fiber, in comparison to the quartz or silicate-based fiber, a relatively high erbium dope concentration can be obtained, thereby enabling the fiber length necessary for amplification can be reduced. Particularly, the fluoride-based fiber is preferably used for the last-stage optical fiber amplifier (optical fiber amplifier 25 shown in Fig. 2). The reduced fiber length enables mitigation in the wavelength width expansion due to the nonlinear effects during pulsed-beam propagation through the fiber. In addition, the reduced fiber length enables the provision of a narrow-band wavelength width necessary for, for example, the exposure apparatus. The narrow-band light source offers an advantage, particularly, when it is used in an exposure apparatus that

has a large number of openings. For example, the light source is advantageous in the design and manufacture of the projection optical system.

In addition, an optical fiber mainly using phosphate glass or oxidized-bismuth based glass ($Bi_2O_3B_2O_3$) may be used, particularly for the last-stage optical fiber amplifier. With the phosphate-glass optical fiber, the core can be doped at a high concentration with a rare-earth based element(s) (such as erbium (Er), or both the erbium (Er) and ytterbium (Yb)). In this case, in comparison to the conventional silicate glass, the fiber length necessary to obtain the same optical amplification factor is about 1/100 of that with the conventional silica glass. With the oxidized-bismuth based glass optical fiber, in comparison to the conventional silica glass, the amount of doped erbium (Er) can be increased to be 100 or more times of that with the conventional silica glass. In this case, effects similar to those with the phosphate glass can be obtained.

In a case where a wavelength of 1.51 to 1.59 μm is used for the output wavelength of the optical fiber amplifier having the double-structure clads, the fiber core is co-doped with erbium (Er) and ytterbium (Yb) used together as an ion dopant. The co-doping is advantageous to improve the semiconductor-laser excitation efficiency. That is, when the erbium/ytterbium co-doping is performed, high-ytterbium-absorbing wavelength expands near a region of 915 to 975 nm. By using the wavelength near to aforementioned

region, the plurality of semiconductor lasers each having a unique oscillation wavelength are connected through wavelength division multiplexing (WDM) and coupled to the first clad. As a result, the plurality of semiconductor lasers can be used as excitation beams, and a high excitation intensity can therefore be implemented.

In designing the doped fiber used in the optical fiber amplifier, a material is preferably selected to obtain a high gain of the optical fiber amplifier in a desired wavelength for an apparatus (such as an exposure apparatus) as in the present example that operates at a predetermined wavelength. For example, a material enabling a high gain to be obtained with desired wavelength, for example 1.548μm, is preferably selected for an amplifying fiber used in an ultraviolet laser apparatus designed to obtain the same output wavelength (193 to 194 nm) as that of the ArF excimer laser.

However, for wavelength-division-multiplexed communication, a communication fiber is designed to have a relatively stable gain in a wavelength region of several tenth of nm near 1.55 μm. As such, for a communication fiber including, for example, erbium-monodoped core as an excitation medium, a method of co-doping a silica fiber with aluminum, phosphorous, and the like is used to implement the stable gain. As such, with the fiber of this type, the gain is not always increased at 1.548 μm. Aluminum as a dopant element has the effect of shifting the peak near 1.55 μm, and phosphorous has the effect of shifting the peak to a short

wavelength side. As such, a small amount of phosphorous can be used as a dopant to increase the gain in a region near 1.547 μm. Similarly, a small amount of phosphorous can be used as a dopant to increase the gain in a region near 1.547 μm to be even higher when using the optical amplifying fiber (such as the double-clad type fiber) having the core doped (co-doped) with both erbium and ytterbium.

a30

Hereinbelow, a description will be made regarding example configurations of the wavelength conversion section 20 used in the ultraviolet light generator of the embodiment shown in Fig. 1.

Fig. 3(a) shows the wavelength conversion section 20 that is capable of obtaining the eighth-order harmonic wave through repetition of the second-order harmonic wave generation. In Fig. 3(a), the laser beam LB4 as the fundamental wave having a wavelength of 1.544 μm (the frequency is represented by "ω") output from the output terminal 19a (shown in an enlarged view) of the fiber bundle 19 is incident on a first-stage nonlinear optical crystal 502. The second-order harmonic wave generation is performed therein to generate the second-order harmonic wave having a twofold frequency 2ω (wavelength: 1/2 of 772 nm) of the frequency ω of the fundamental wave. The generated second-order harmonic wave is then incident on a second-stage nonlinear optical crystal 503 through a lens 505. Similar to the above, through the second-order harmonic wave generation, there is generated fourth-order harmonic wave

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having a twofold frequency of the frequency 2ω of the incident wave, that is, a fourfold frequency 4ω (wavelength: 1/4 of 386 nm) with respect to the fundamental wave. The generated fourth-order harmonic wave is then transferred to a third-stage nonlinear optical crystal 504 through a lens 506. Similarly, through the second-order harmonic wave generation, there is generated eighth-order harmonic wave having a twofold frequency of the frequency 4ω of the incident wave, that is, an eightfold frequency 8ω (wavelength: 1/8 of 193 nm) with respect to the fundamental wave. The eighth-order harmonic wave is output as laser beam LB5. Thus, the example configuration performs wavelength modulations in the following order: fundamental wave (wavelength: 1.544 μm) → second-order harmonic wave (wavelength: 772 nm) → fourth-order harmonic wave (wavelength: 386 nm) → eighth-order harmonic wave (wavelength: 193 nm).

Example nonlinear optical crystals usable for the above-described wavelength conversion include a LiB_3O_5 (LBO) crystal for the nonlinear optical crystal 502 used to convert the fundamental wave into the second-order harmonic wave, a LiB_3O_5 (LBO) crystal for the nonlinear optical crystal 503 used to modulate the second-order harmonic wave into the fourth-order harmonic wave, and a $Sr_2Be_2B_2O_7$ (SBBO) crystal for the nonlinear optical crystal 504 used to convert the fourth-order harmonic wave into the eighth-order harmonic wave. In the present example, "non-critical phase matching" (NCPM) is employed for the LBO-crystal used conversion of the

fundamental wave into the second-order harmonic wave. The NCPM method regulates the temperature of the LBO crystal for phase matching for the wavelength conversion. The NCPM method does not cause an angular displacement (so-called "walk-off") between the fundamental wave and the second-order harmonic wave in the nonlinear optical crystal, thereby allowing conversion into the second-order harmonic wave with high efficiency. As such, the NCPM method is advantageous in that the generated second-order harmonic wave is not influenced by walk-off-caused beam deformation.

Sub A31

Referring to Fig. 8(a), a converging lens, which is effective for improving the incidence efficiency of laser beam LB4, is preferably provided between the fiber bundle 19 and the nonlinear optical crystal 502. In this case, each of the optical fibers constituting the fiber bundle 19 has a mode diameter (core diameter) of about 20 μm, and a region where the conversion efficiency in the nonlinear optical crystal has a size of about 200 μm. As such, a lens with a very low magnification of about 10× magnification may be provided in units of the optical fiber to converge the laser beam output from each of the optical fibers into the nonlinear optical crystal 502. This applies also to other example configurations described below.

Fig. 3(b) shows a wavelength conversion section 20A that is capable of obtaining the eighth-order harmonic wave by combining the second-order harmonic wave generation and sum frequency generation. Referring to Fig. 3(b), the laser beam

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~~LB4 (fundamental wave) having a wavelength of 1.544 μm output from the output terminal 19a of the fiber bundle 19 is incident on a first-stage nonlinear optical crystal 507 formed of the LBO crystal and controlled by the NCPM method. In the crystal 507, there is generated the second-order harmonic wave according to the second-order harmonic wave generation. In addition, a part of the fundamental wave is transmitted as is through the nonlinear optical crystal 507. Both the fundamental wave and second-order harmonic wave in a linearly polarized state are transmitted trough a wavelength plate 508 (for example, a 1/2 wavelength plate), and only the fundamental wave is output in a 90-degree rotated direction of polarization. The fundamental wave and the second-order harmonic wave individually pass through a lens 509 and are incident on a nonlinear optical crystal 510.~~

In the nonlinear optical crystal 510, there is generated the third-order harmonic wave from the second-order harmonic wave generated in the first-stage nonlinear optical crystal 507 and the fundamental wave transmitted without being converted. The above generation is performed according to the aforementioned sum frequency generation. While the LBO crystal is used for the nonlinear optical crystal 510, it is used in NCPM with a temperature different from that of the first-stage nonlinear optical crystal 507 (LBO crystal). The third-order harmonic wave generated in the nonlinear optical crystal 510 and the second-order harmonic wave transmitted without being converted are isolated by a dichroic mirror 511.

Then, the third-order harmonic wave reflected by the dichroic mirror 511 is transmitted through a lens 513 to be incident on a third-stage nonlinear optical crystal 514 formed of a β-BaB_2O_4 crystal (BBO crystal). Therein, the third-order harmonic wave is converted by the second-order harmonic wave generation into the sixth-order harmonic wave.

The second-order harmonic wave transmitted through the dichroic mirror is incident on a dichroic mirror 516 via a lens 512 and a mirror M2. In addition, the sixth-order harmonic wave obtained through the nonlinear optical crystal 514 is incident on the dichroic mirror 516 via a lens 515. In this step, the second-order harmonic wave and the sixth-order harmonic wave are coaxially combined, and a composition thereof is incident on a fourth-stage nonlinear optical crystal 517 formed of the BBO crystal. In the nonlinear optical crystal 517, there is generated the eighth-order harmonic wave (wavelength: 193 nm). The eighth-order harmonic wave is output as an ultraviolet laser beam LB5. A $CsLiB_6O_{10}$ (CLBO) crystal may be used in place of the BBO crystal for the nonlinear optical crystal 517. Thus, the wavelength conversion section 20A performs wavelength conversion in the following order: fundamental wave (wavelength: 1.544 μm) → second-order harmonic wave (wavelength: 772 nm) → third-order harmonic wave (wavelength: 515 nm) → sixth-order harmonic wave (wavelength: 257 nm) → eighth-order harmonic wave (wavelength: 193 nm).

As described above, the present example has the configuration in which one of the sixth-order harmonic wave and second-order harmonic wave passes through a split optical path and is then incident on the fourth-stage nonlinear optical crystal 517. In the configuration, the lenses 515 and 512 individually converging the sixth-order harmonic wave and the second-order harmonic wave into the fourth-stage nonlinear optical crystal 517 can be disposed on optical paths different from each other. In this case, the sixth-order harmonic wave generated in the third-stage nonlinear optical crystal 514 is shaped by the walk-off phenomenon to have an elliptical cross section. As such, beam-shaping is preferably performed for the sixth-order harmonic wave to obtain a high conversion efficiency with the fourth-stage nonlinear optical crystal 517. To implement the above, as in the present example, the individual lenses 515 and 512 are preferably disposed on different optical paths. This enables a cylindrical lens pair to be used for the converging lens 515, thereby enabling the beam-shaping for the sixth-order harmonic wave to easily be implemented. Hence, the conversion efficiency can be improved by increasing overlapping portions with the second-order harmonic wave in the fourth-stage nonlinear optical crystal 517 (BBO crystal).

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The configuration between the second-stage nonlinear optical crystal 510 and the fourth-stage nonlinear optical crystal 517 is not limited to that shown in Fig. 3(b). This configuration may be arbitrarily arranged as long as it has

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the same optical path lengths for the sixth-order harmonic wave and the second-order harmonic wave to cause the sixth-order harmonic wave and the second-order harmonic wave to be incident on the fourth-stage nonlinear optical crystal 517. Moreover, for example, the third-stage and fourth-stage nonlinear optical crystals 514 and 517 may be disposed on the same optical axis of the second-stage nonlinear optical crystal 510. In this configuration, the third-stage nonlinear optical crystal 514 is used to convert only the third-order harmonic wave into the sixth-order harmonic wave according to the second-order harmonic wave generation, and the converted harmonic wave and the non-converted second-order harmonic wave together are incident on the fourth-stage nonlinear optical crystal 517. This configuration avoids the necessity of using the dichroic mirrors 511 and 516. The above is the same for an example configuration of Fig.4 described below.

Sub A33

For the individual wavelength conversion sections 20 and 20A shown in Fig. 3(a) and (b), the average output power of the per-channel eighth-order harmonic waves (wavelength: 193 nm) were experimentally obtained. As described in the above-described embodiment, the output of the fundamental wave at each of the channel output terminal is characterized by a peak power of 20 kW, a pulsewidth of 1 ns, a pulse repetition frequency of 100 kHz, and an average output power of 2W. As a result, the per-channel average output powers of the eighth-order harmonic waves were 229 mW in the

Sub A33

wavelength conversion section 20 shown in Fig. 3(a), and 38.3 mW in the wavelength conversion section 20A shown in Fig. 3(b). Accordingly, the average output powers from the bundle of all the 128 channels are 29 W in the wavelength conversion section 20, and 4.9 W in the wavelength conversion section 20A. As such, in either of the wavelength conversion sections 20 and 20A, ultraviolet light having a wavelength of 193 nm beam, which is sufficient as an exposure-apparatus-dedicated light source can be provided.

Sub A34

Hereinbelow, a description will be made regarding an example configuration of a wavelength conversion section that enables ultraviolet light having substantially the same wavelength as that of the F_2 laser (wavelength: 157 nm). To implement the above, as the wavelength conversion section 20, the configuration may be arranged to use a wavelength conversion section capable of generating the tenth-order harmonic wave with 1.57 µm wavelength of the fundamental wave generated in the single wavelength oscillatory laser 11 shown in Fig. 1(a).

Fig. 4(a) shows a wavelength conversion section 20B that enables the tenth-order harmonic wave to be generated through combination of the second-order harmonic wave generation and the sum frequency generation. Referring to Fig. 4(a), the fundamental wave of the laser beam LB4, having a wavelength of 1.57 µm, which has been output from the output terminal 19a of the fiber bundle 19, is incident on a first-stage nonlinear optical crystal 602 formed of the LBO crystal, and

is converted into the second-order harmonic wave according to the second-order harmonic wave generation. The second-order harmonic wave is then incident on a second-stage nonlinear optical crystal 604 formed of LBO via a lens 603, and is converted into the fourth-order harmonic wave according to the second-order harmonic wave generation; and a part of the second-order harmonic wave is transmitted therethrough without being converted.

Both the fundamental wave and second-order harmonic wave transmitted through the second-stage nonlinear optical crystal 604 are directed to a dichroic mirror 605. The fourth-order harmonic wave reflected is reflected by a mirror M1, passes through a lens 608, and is incident on a third-stage nonlinear optical crystal 609 formed of the $Sr_2Be_2B_2O_7$ (SBBO) crystal, and is converted thereby into the eighth-order harmonic wave according to the second-order harmonic wave generation. On the other hand, the second-order harmonic wave transmitted through the dichroic mirror 605 is incident on a dichroic mirror 607 through a lens 606 and a mirror M2. The eighth-order harmonic wave obtained through the third-stage nonlinear optical crystal 609 is also incident on the dichroic mirror 607 via a lens 610. Then, the second-order harmonic wave and the eighth-order harmonic wave are coaxially combined, and the combined harmonic waves are incident on a fourth-stage nonlinear optical crystal 611 formed of the SBBO crystal. Therein, the tenth-order harmonic wave (wavelength: 157 μm) can be generated from the

eighth-order harmonic wave and the second-order harmonic wave according to the sum frequency generation. The tenth-order harmonic wave is output as an ultraviolet laser beam LB5. Thus, the wavelength conversion section 20B performs wavelength conversion in the order: fundamental wave (wavelength: 1.57 µm) → second-order harmonic wave (wavelength: 785 nm) → fourth-order harmonic wave (wavelength: 392.5 nm) → eighth-order harmonic wave (wavelength: 196.25 nm) → tenth-order harmonic wave (wavelength: 157 nm).

In addition, a different method may be employed to obtain ultraviolet light having substantially the same wavelength as the wavelength (157 nm) of the F_2 laser. A method can be envisaged that uses a wavelength conversion section as the wavelength conversion section 20, which is capable of generating the seventh-order harmonic wave with the 1.099-µm wavelength of the fundamental wave generated in the single wavelength oscillatory laser 11.

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Fig. 4(b) shows a wavelength conversion section 20C that enables the seventh-order harmonic wave to be generated through combination of the second-order harmonic wave generation and the sum frequency generation. Referring to Fig. 4(b), the laser beam LB4 (fundamental wave), having a wavelength of 1.099 µm, which has been output from the output terminal 19a of the fiber bundle 19, is incident on a first-stage nonlinear optical crystal 702 formed of the LBO crystal, and the second-order harmonic wave is generated

therein according to the second-order harmonic wave generation. A part of the fundamental wave is transmitted as is therethrough. Both the fundamental wave and second-order harmonic wave transmits in a linearly polarized state transmits through a wavelength plate 703 (such as a 1/2 wavelength plate), and only the direction of polarization of only the fundamental wave is rotated through 90 degrees. The fundamental wave and the second-order harmonic wave is led through a lens 704 to be incident on a second nonlinear optical crystal 705 formed of the LBO crystal. The third-order harmonic wave is generated therein according to the sum frequency generation, and a part of the second-order harmonic wave is transmitted as is therethrough.

The second-order harmonic wave generated from the second nonlinear optical crystal 705 and the third-order harmonic wave are split by a dichroic mirror 706. The third-order harmonic wave transmitted therethrough is incident on a dichroic mirror 708 via a lens 707 and a mirror M2. On the other hand, the second-order harmonic wave reflected by the dichroic mirror 706 passes through a mirror M1 and a lens 709, is incident on a third nonlinear optical crystal 710, and is converted therein into the fourth-order harmonic wave. The fourth-order harmonic wave is led through a lens 711 to be incident on the dichroic mirror 708. The third-order harmonic wave and fourth-order harmonic wave coaxially combined by the dichroic mirror 708 are incident on a fourth nonlinear optical crystal 712 formed of the SBBO

crystal, and are therein converted into the seventh-order harmonic wave (wavelength: 157 nm) according to the sum frequency generation. The seventh-order harmonic wave is output as an ultraviolet laser beam LB5. Thus, the present example configuration performs wavelength conversion in the following order: fundamental wave (wavelength: 1.099 μm) → second-order harmonic wave (wavelength: 549.5 nm) → third-order harmonic wave (wavelength: 366.3 nm) → fourth-order harmonic wave (wavelength: 274.8 nm) → seventh-order harmonic wave (wavelength: 157 nm).

Moreover, other than the wavelength conversion sections 20 to 20C can also obtain the eighth-order harmonic wave, the tenth-order harmonic wave, or the seventh-order harmonic wave by diversely combining nonlinear optical crystals. It is preferable to use the one among these that can improve the conversion efficiency and that can simplify the configuration.

Sub A26

As is apparent from Fig. 1(a), in the above-described embodiment, the combined light of the outputs of the n optical amplifier units 18-1 to 18-n in the m-group is converted in wavelength by using the single wavelength conversion section 20. Alternatively, however, the configuration may be arranged such that, for example, m' units (m' = "2" or larger inger) wavelength conversion sections are provided. In the alternative configuration, the outputs of the m-group optical amplifier units 18-1 to 18-n are divided in units of n' outputs into m' groups (n·m = n'·m'), the wavelength conversion is

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performed for one of the wavelength conversion section in units of one of the groups, and the obtained m' ultraviolet light beams (in the present example, m' = "4", "5", or the like) are combined. Thus, the wavelength conversion section 20 is not limited to that having the above-described configuration. Moreover, for example, a CBO crystal (CsB_3O_5), an $Li_2B_4O_7$ (LBO), a KAB ($K_2Al_2B_4O_7$), or a GdYCOB ($Gd_xY_{1-x}Ca_4O(BO_3)_3$), may be used as an alternative crystal for the nonlinear optical crystal.

According to the ultraviolet light generator of the above-described embodiment, the diameter of the output terminal of the fiber bundle 19, shown in Fig. 1(a), even with all the channels being included, is about 2 mm or smaller. As such, one or several units of the wavelength conversion sections 20 are sufficient to perform the wavelength conversion of all the channels. In addition, since flexible optical fibers are used for the output terminals, the flexibility in configuration is very high. For example, the configuration sections such as the wavelength conversion section, the single wavelength oscillatory laser, and the splitter, can be separately disposed. Consequently, the ultraviolet light generator of the present example enables the provision of an ultraviolet laser device that is inexpensive and compact, and has a low spatial coherence while it is of a single wavelength type.

Moreover, according to the above-described embodiment, as shown in Fig. 6, in the optical modulating device 12 shown

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Fig. 1(a), the continuous light of a predetermined level is output even in period in which the ultraviolet light (laser beam LB5) is switched "OFF". Thereby, optical surges are prevented from occurring in the rear-stage optical fiber amplifiers 13, 22, and 25, and the output power of the desired value can be obtained immediately after the ultraviolet light is switched "ON". Instead of outputting the continuous light in the period in which the ultraviolet light is "OFF", the arrangement may be made to output a pulsed beam having a duty ratio (ratio of the high level "1" period to the pulse cycle) that is 10 times or higher, and preferably, 100 times or higher in comparison to those in the period in which the ultraviolet light is "ON". Also in this case, the peak level of the pulsed beam in the "OFF" period becomes 1/10 or lower or 1/100 or lower by controlling the average levels in the periods in which the ultraviolet light is switched "ON" and "OFF" to be substantially the same. Consequently, similar to the case of outputting the continuous light, optical surges are mitigated, and the efficiency of conversion into the ultraviolet light in the "OFF" period can be controlled to be substantially zero.

Hereinbelow, a second embodiment of the present invention will be described with reference to Figs. 7 to 9. The present embodiment is different from the embodiment shown in Fig. 1(a) in portions of the configurations from the single wavelength oscillatory laser 11 to the optical fiber amplifier 13. A description will therefore be made regarding the

A36 ~~different portions.~~

Fig. 7 shows essential portions of the present embodiment. Referring to Fig. 7, a laser beam LB1 having a wavelength of 1.544 μm (which hereinbelow will be represented by λ_1) that has been output from the single wavelength oscillatory laser 11 is incident on a wavelength division multiplexing device (WDM device) 52 through an optical fiber 53A. A laser beam LBR having a wavelength λ_2, which is different from the laser beam having the wavelength λ_1 that has been output from a semiconductor laser 51 provided as an auxiliary light source, is incident on the WDM device 52 through an optical fiber 53B. A laser beam formed of the laser beams coupled in the WDM device (52) is incident on an optical modulating device 12 via an optical fiber 53C. Then, the laser beam is subjected to pulse modulation or amplitude modulation (level modulation) in the optical modulating device 12, and an output laser beam LB2 is incident on an optical fiber amplifier 13.

The wavelength λ_2 of the laser beam LBR output from the auxiliary light source is set to a wavelength zone that can be amplified by the optical fiber amplifier 13 and the optical fiber amplifiers 22 and 25 on the rear-stage optical amplifier units 18-1 to 18-n. Concurrently, the wavelength λ_2 is set to a wavelength of which the efficiency of conversion into ultraviolet light in the wavelength modulator section 20 substantially becomes zero. In a case assumed such that light having substantially the same wavelength as that of an ArF

excimer laser (wavelength = 193 nm) is generated in the form of ultraviolet light, a wavelength zone that can be amplified by the optical fiber amplifiers 13, 22, and 25 are in a range of about 1.53 to 1.56 μm. For this reason, the wavelength λ_2 of the laser beam LBR is set to, for example, either about 1.53 μm or about 1.56 μm.

Sub A37

In the present embodiment, as shown in Figs. 8(a) and 8(b), a first usage method is arranged such that the laser beam LB1 is turned off, and the laser beam LBR is controlled to continually emit in the "OFF" period in which the ultraviolet light is not output, and the laser beam LB1 is controlled to continually emit, and the laser beam LBR is turned off in the "ON" period in which the ultraviolet light is output. That is, the original laser beam LB1 and the auxiliary laser beam LBR are controlled to emit with opposite phases. In addition, as shown in Fig. 8(c), an application voltage V12 as a driving signal fed from the driver 3 to the optical modulating device 12 is set in a pulse state only in the "ON" period in which the ultraviolet light is output. Thereby, as shown in Fig. 8(d), in the "ON" period, the laser beam LB2 to be output from the optical modulating device 12 is modulated into a pulse train (wavelength λ_1) of a frequency of about 100 kHz having a peak level LB and a width of about 1 ns. In the "OFF" period, the laser beam LB2 is modulated into continuous light (wavelength λ_2) of a level LA. The level LA in this case is set such that, for example, the average output power of the laser beam that have been output from the

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last-stage optical fiber amplifier 25 are substantially the same in the "ON" and "OFF" periods. Thereby, no optical surge occurs in, for example, the optical fiber amplifier 25. In addition, the conversion efficiency in the "OFF" period in which the ultraviolet light is not output substantially becomes zero, thereby avoiding a case where an unnecessary laser beam is output.

In the present embodiment, as shown in Figs. 9(a) and 9(b), a second usage method is arranged such that the original laser beam LB1 and the auxiliary laser beam LBR are controlled to emit with opposite phases. In addition, an application voltage V12 (driving signal) fed from the driver 3 to the optical modulating device 12 is regularly set to be a pulse shape as shown in Fig. 9(c). Thereby, as shown in Fig. 9(d), in the "ON" period, similar to the case shown in Fig. 8(d), the laser beam LB2 output from the optical modulating device 12 is modulated into a pulse train (wavelength λ_1); and also in the "OFF" period, the laser beam LB2 is modulated into a similar pulse train (wavelength λ_2). Also in this arrangement, no optical surge occurs in, for example, the optical fiber amplifier 25, and an unnecessary laser beam is output in the "OFF" period.

For the selection of desired one of the control methods shown in Figs. 8 and 9, the determination is preferably made according to the wavelength characteristics of the optical modulating device 12 and the wavelength λ_2 of the auxiliary laser beam LBR. That is, one of the control methods may

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preferably be selected through which only light of the wavelength λ_2 is output from the optical modulating device 12 in the period ("OFF" period) in which the ultraviolet light is not output.

In the embodiment shown in Fig. 7, the WDM device 52 is disposed in an input portion of the optical modulating device 12. However, as shown in Fig. 11, the WDM device 52 may be disposed in an output portion of the optical modulating device 12. In this case, a laser beam LBM having the wavelength λ_1 that has been output from the optical modulating device 12 is coupled in the WDM device 52 to the auxiliary laser beam LBR having the wavelength λ_2, and the laser beam LB2 thus obtained is fed to the optical fiber amplifier 13. Also in the configuration example shown in Fig. 11, occurrence of optical surges in the optical fiber amplifiers is mitigated, and occurrence of unnecessary ultraviolet light can be prevented by controlling the laser beam LB1 output from the single wavelength oscillatory laser 11 and the laser beam LBR to be emitted with the opposite phases.

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Hereinbelow, a third embodiment of the present invention will be described with reference to Fig. 10. Also the present embodiment is different from the embodiment shown in Fig. 1(a) in portions of the configurations from the single wavelength oscillatory laser 11 to the optical fiber amplifier 13. A description will therefore be made regarding the different portions.

Fig. 10 shows essential portions of the present

embodiment. Referring to Fig. 10, a laser beam LB1 (which is assumed to be linear polarization light) having a wavelength of 1.544 µm that has been output from the single wavelength oscillatory laser 11 is incident on a polarized-wave combining device 55 for coaxially combining two light beams of different polarized states, and a laser beam LBP is incident on the polarized-wave combining device 55. The laser beam LBP has a wavelength of 1.544 µm, is output from a semiconductor laser 54 provided as an auxiliary light source, and is linearly polarized in the direction perpendicular to the laser beam LB1. A laser beam formed of the laser beams coupled in the polarized-wave combining device 55 is then incident on an optical modulating device 12. Then, the laser beam is subjected to pulse modulation or amplitude modulation (level modulation) in the optical modulating device 12, and an output laser beam LB2 is incident on an optical fiber amplifier 13.

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~~In this case, in each of the optical fibers used in the present embodiment, the polarized state of the light propagating inside thereof is assumed to be preserved to some extent. In addition, the angle and other conditions of each optical fiber is assumed to be set such that a laser beam LB4 to be finally output from the optical fiber bundle 19 shown in Fig. 1(a) is in a polarized state that enables the maximum conversion efficiency to be obtained in the period ("ON" period) in which ultraviolet light is output from the wavelength conversion section 20. In addition, in the~~

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configuration example shown in Fig. 10, the polarization direction of the laser beam LB1 is set to a direction such that the maximum conversion efficiency can be obtained in the wavelength conversion section 20. The polarization direction of the laser beam LBP output from the auxiliary light source is set to a direction such that the conversion efficiency is minimized in the wavelength conversion section 20.

Similar to the embodiment shown in Fig. 7, in the above-described embodiment, the laser beam LB1 and the laser beam LBP are emitted with opposite phases in the period ("ON" period) in which the ultraviolet light is output and in the period ("OFF" period) in which the ultraviolet light is not output. In addition, the drive method for the optical modulating device 12 has two types. The one type controls the optical modulating device 12 to output the pulsed beam only in the "ON" period, as shown in Fig. 8; and the other type controls the optical modulating device 12 to regularly output the pulsed beam, as shown in Fig. 9. For the selection of desired one of the control methods shown in Figs. 8 and 9, the determination is preferably made according to the wavelength characteristics of the optical modulating device 12 and the polarized state of the auxiliary laser beam LBP. That is, one of the control methods may preferably be selected through which only the laser beam LBP is output from the optical modulating device 12 in the period ("OFF" period) in which the ultraviolet light is not output. Thereby,

substantially constant outputs can regularly be obtained in the individual optical fiber amplifiers 13, 22, and 25, and optical surges are prevented from occurring. In addition, the efficiency of conversion in the wavelength conversion section 20 with respect to the ultraviolet light substantially becomes zero in the "OFF" period, thereby avoiding a case where an unnecessary laser beam is output.

In the embodiment shown in Fig. 10, the polarized-wave combining device 55 is disposed in an input portion of the optical modulating device 12. However, as shown in Fig. 12, the polarized-wave combining device 55 may be disposed in an output portion of the optical modulating device 12. In this case, a linearly polarized laser beam LBM that has been output from the optical modulating device 12 is coupled in the polarized-wave combining device 55 to the laser beam LBP of which the polarization direction is perpendicular thereto and which has been output from the semiconductor laser 54, and the coupled laser beam LB2 thereby obtained is fed to the optical fiber amplifier 13. Also in the configuration examle shown in Fig. 12, occurrence of optical surges in the optical fiber amplifiers is mitigated, and occurrence of unnecessary ultraviolet light can be prevented by controlling the laser beam LB1 that has been output from the single wavelength oscillatory laser 11 and the laser beam LBP to be emitted with the opposite phases.

Hereinbelow, an example exposure apparatus using the ultraviolet light generator shown in Fig. 1(a) will be

Sub A40

described. Fig. 13 shows an exposure apparatus of the present example. Referring to Fig. 13, component members provided between the single wavelength oscillatory laser 11 and the m-group optical amplifier units 18-1 to 18-n in the ultraviolet light generator shown in Fig. 1(a) are used for an exposure light source 171. The ultraviolet light generator is tuned to be capable of converting the laser beam LB5 finally output into light in an ultraviolet region with one of wavelengths of 193 nm, 157 nm, and others.

Most of a laser beam (fundamental wave) output from a light-source mainbody section 171 is fed to an illumination system 162 via a coupling-dedicated optical fiber 173 and a wavelength selection section 172. The rest of the laser beam is fed to an alignment system (described below in detail) via a coupling-dedicated optical fiber 178. The coupling-dedicated optical fibers 173 and 178 individually correspond to beams obtained by splitting the fiber bundle 19 shown in Fig. 1(a).

The wavelength selection section 172 (which corresponds to the wavelength conversion section 20 shown in Fig. 1(a)) converts the wavelength of the fundamental wave received from a light-source mainbody section 171, and outputs ultraviolet-region exposure light formed of the laser beam LB5. The illumination system 162 is configured of, for example, an optical integrator (homogenizer) for homogenizing illuminance distributions of the exposure light, an aperture diaphragm, a field diaphragm (reticle blind), and

Sub a40

a condenser lens. In the aforementioned configuration, the exposure light output from the illumination system 162 illuminates a slit-like illumination region of a pattern surface of a reticle 163 set as a mask to provide a homogeneous illuminance distribution. In the present example, since the spatial coherence of the exposure light is so low that the configuration of a member for reducing the spatial coherence in the illumination system 162 can be simplified, and the exposure apparatus can therefore be further miniaturized.

The reticle 163 is set on a reticle stage 164. The exposure light transmitted through the reticle 163 is used to project a demagnified image of a pattern in the illumination region onto a wafer 166 (exposure-target substrate) via a projection optical system 165. The projection is performed at a magnification M_{RW} (for example, 1/4, 1/5, 1/6, or the like). For the projection optical system 165, any one of a dioptric system, a reflection system, or a catadioptric system is usable. However, when using vacuum ultraviolet light for the exposure light, since materials having high transmittance is limited, the catadioptric system may preferably used to improve the imaging performance. The wafer 166 is coated with photoresist, and is a disc-like substrate, such as a semiconductor (silicon or the like) or a SOI (silicon on insulator).

The wafer 166 is held on a wafer stage 167, and the three-dimensional position of the wafer 166 is defined by the wafer stage 167 driven by a drive section 169. In addition,

the reticle stage 164 is driven by a driving mechanism 168 in a state of being two-dimensionally movable and rotatable. The driving section 169 and the driving mechanism 168 are controlled by a primary control system 177. At the time of exposure, the wafer 166 is positioned through stepping movements of the wafer stage 167. Thereafter, the reticle 163 is scanned via the reticle stage 164 in a predetermined direction with respect to the illumination region, and the image of the pattern of the reticle 163 is transferred on each shot region of the wafer 166 according to step-and-scan method. In this case, the step-and-scan method performs scanning the wafer 166 via the wafer stage 167 by using the magnification M_{RW} as a velocity ratio. Thus, the exposure apparatus of the present example is of a scan-exposure type. However, it should be apparent that the exposure light source 171 can be applied also to a exposure apparatus, such as a stepper, of a full-field-exposure type.

In the above-described case, since the exposure light source 171 and the wavelength selection section 172 (light-source system) of the present example are small, it may be immobilized together with at least a portion (such as the wavelength selection section 172) of the light-source system on a frame provided for supporting the illumination system 162. Alternatively, the exposure light source 171 may be independently disposed. However, a powersupply and the like to be coupled to the exposure light source 161 are preferably disposed separately.

As described above, the exposure apparatus using the ultraviolet light generator of the present example is smaller in comparison with the conventional one using another type (exposure apparatus using, for example, the excimer laser or the arrayed laser). In addition, since the exposure apparatus is configured of elements coupled using the optical fibers, the exposure apparatus has a high flexibility in disposition of the individual units used for the configuration thereof.

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Exposure-light-amount control in the above-described scan-exposure operation may be implemented in the following manner. Control is performed for at least one of the pulse repetition frequency f, which is defined by the optical modulating device 12 shown in Fig. 1(a), and the interchannel delay time, which is defined by the delaying devices (optical fibers 15-1 to 15-m, and 17-1 to 17-n). The control is thus performed to cause the exposure light source 171 to oscillate a plurality of pulsed beams at equal time intervals during scan-exposure operation. In addition, according to the sensitivity property of the photoresist, at least one of the optical intensity of the pulsed beam on the wafer 166, the scan speed for the wafer 166, the pulsed-beam oscillation interval (frequency), and the width of the pulsed beam in the scan direction for the wafer 166 (that is, an radiation region thereof) to thereby control the integrated luminous quantity of a plurality of pulsed beams irradiated in a period in which the individual points of the wafer traverse the radiation

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region. At this time, in consideration of the throughput, least one of other control parameters representing the pulsed-beam optical intensity, the oscillation frequency, and the radiation region width is preferably controlled so that the scan speed for the wafer 166 is substantially maintained to be the maximum speed of the wafer stage 167.

In addition, in the present example, since the coupling-dedicated optical fiber 173 and a coupling-dedicated optical fiber 178 are used, the light-source mainbody section 171 can be provided outside of the exposure apparatus mainbody. The configuration built as described above enables major configuration portions involving heat generation to be disposed outside of the exposure apparatus mainbody. The major configuration portions include an excitation-dedicated semiconductor laser for the optical fiber amplifier, a driving powersupply for the semiconductor laser, and a temperature controller. As such, the configuration enables the mitigation or avoidance of heat-attributed problems, such as a problem of optical-axis misalignment that can occur when the exposure apparatus mainbody is influenced by heat generated in the ultraviolet light generator provided as the exposure light source.

In addition, the reticle stage 164 of the present example is configured so that it is driven by the driving mechanism 168 to be movable in the X and Y directions and to be finely rotatable. Further, a reference mark plate FM is provided on the wafer stage 167. The reference mark plate

FM is used for, for example, baseline measurement described below. Moreover, the present example includes an alignment system 180 provided for detecting an alignment mark on the reticle 163, and an alignment system 181 of an off-access method that operates without the projection optical system 165.

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In the present example, a laser beam (fundamental wave) from the light-source mainbody section 171 is fed to a wavelength conversion section 179 for the alignment system 180 via an optical fiber 178. For the wavelength conversion section 179, the present example uses a wavelength conversion section that is similar to the wavelength conversion section 20 shown in Fig. 1(a) and that is relatively small. The wavelength conversion section 179 is integrally provided on the frame that holds the alignment system 180, in which laser beam LB5 having the same wavelength as that of the exposure light that has been output from the wavelength conversion section 179 is used as illumination light AL.

The above-described arrangement avoids the necessity of providing an light source for the alignment system 180. In addition, the reference mark or the alignment mark can be detected by using illumination light having the same wavelength as that of exposure light, and accurate mark detection can be implemented. That is, the alignment system 180 radiates illumination light AL having the same wavelength of exposure light onto the alignment mark and onto a reference mark on the reference mark plate FM through the projection

optical system 165. In addition, the alignment system 180 uses an image-capturing device (CCD) to receive light generated from the aforementioned two marks, and is used for, for example, alignment of the reticle 163 and baseline measurement of the alignment system 181.

The off-access alignment system 181 radiates white light (broad band light) having a wavelength width of about 550 to 750 nm onto the alignment mark on the wafer 166. In addition, the alignment system 181 causes an image of an index mark and an image of the alignment mark to be imaged on the image-capturing device (CCD), and detects positional displacements of the two marks.

In this case, when the alignment systems 180 and 181 are used to individually detect the reference mark on the reference mark plate FM, the amount of the baseline (gap between the detection center and the exposure center) can be measured from the detection results. Alignment of each shot region of the wafer 166 is implemented at high accuracy according to this result and the measurement result of the alignment system 181. The baseline measurement is performed prior to the start of exposure of the wafer. However, the baseline measurement may be performed each time the wafer is replaced; or alternatively, the measurement may be performed at a ratio of about one time with respect to the exposure operation for a plurality of wafers. However, the baseline is inevitably measured after the reticle has been replaced.

The optical fiber (including the optical fiber

amplifier and the like) used in the above-described embodiment may preferably be covered with a low-degassing material, such as Teflon or fluorine-based resin. Foreign matters (including fibrous matters and the like) occurred from the optical fiber can be contaminants that contaminates, and the optical fiber is covered as described above to prevent the occurrence of the contaminants. However, instead of covering the optical fiber with the Teflon or the like, the optical fibers disposed in chambers may be collectively stored in a stainless steel housing.

The exposure apparatus of the above-described embodiment shown in Fig. 13 may include a spatial-image measuring system. The spatial-image measuring system may be such that the mark provided on the reticle 163 and the reference mark provided on the reticle stage 164 are illuminated with illumination light having the same wavelength, and a mark image formed by the projection optical system 165 is detected through an opening (such as a slit) provided on the wafer stage 167. In this case, for a light source generating the illumination light for the spatial-image measuring system, a light source having the same configuration as that of the above-described light source (171 and 179) may be separately provided. Alternatively, the exposure-dedicated light source formed of the members including the exposure light source 171 and the illumination system 162 may be shared.

The projection exposure apparatus of the above-

mentioned embodiment can be manufactured in the following manner. The illumination optical system and the projection optical system, which are formed to include the plurality of lenses, are built into the exposure apparatus mainbody, and are optically adjusted. The configuration members such as the reticle stage and the projection optical system, which are formed of many mechanical components, are assembled to the exposure apparatus mainbody; and wirings, pipings, and the like are connected. In addition, the total adjustment (including electrical adjustment and operational verification) is performed. The exposure apparatus is preferably manufactured by a so-called "clean room" for which environmental factors, such as the temperature and the cleanliness are managed.

The semiconductor device is manufactured according to various processing steps. The processing steps including a step of designing functions and performance of the device; a step of manufacturing a reticle according to the aforementioned step; a step of manufacturing a wafer from a silicon material; a step of exposing the wafer to a pattern of the reticle by using the exposure apparatus of the above-described embodiment; a step of device assembly (the step includes a dicing step, a bonding step, and a packaging step); and an inspecting step.

Moreover, the present invention may also be applied to the manufacture of various other devices. The devices include display devices such as a liquid crystal display

device and a plasma display device; thin-film magnetic disks; micromachines; and various devices such as DNA chips. Moreover, the present invention may be applied to the manufacture of a photomask for a projection exposure apparatus.

The laser device in the exposure apparatus of the present invention may also be applied to a laser-repairing unit used to cut a part (such as a fuse) of a circuit pattern formed on a wafer. In addition, the laser device may also be applied to a testing apparatus that uses visible light or infrared light. In this case, the above-described wavelength conversion section need not be built in the laser device. Thus, the present invention is effective for not only the ultraviolet light generator, but laser devices that generate fundamental waves of either a visible region or an infrared region and that do not have a wavelength conversion section.

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~~In the above-described embodiment, description has been made that the laser device shown in Fig. 1 is used either as the exposure-dedicated light source or as the light source of the alignment system or the spatial-image measuring system. However, the laser device may be used as a regulating light source of a detecting system or an optical system for marks other than the above. In addition, the laser device may be used not only as the light source of the exposure apparatus, the testing apparatus, or the like used in the device-manufacturing step, but also as a light source of various other apparatuses, regardless of the use and like thereof (an~~

~~example is an conventional apparatus using an excimer laser as a light source, such as a laser medical treatment apparatus for performing medical treatment for, for example, the near site and the astigmatism, by correcting, for example, the curvature or the irregularity of the cornea).~~

The present invention regarding the exposure apparatus may be applied to a proximity exposure apparatus that performs exposure for a mask pattern in a state where a mask and a substrate are proximately set without using a projection optical system.

The present invention is not limited to the above-mentioned embodiments, and the invention may, as a matter of course, be embodied in various forms without departing from the gist of the present invention. Furthermore, the entire disclosure of Japanese Patent Application 11-258132 filed on September 10, 1999 including description, claims, drawings and abstract are incorporated herein by reference in its entirety.

Industrial Applicability

According to the present invention, since the optical fiber amplifiers are used, the exposure apparatus including a small laser device as a laser light source having a high maintainability can be provided.

In addition, in the period in which the ultraviolet light is output, the laser beam that has been output from the laser light source generation section is pulse-modulated, and is then

fed to the optical amplification section. Moreover, even in the period in which the ultraviolet light is not output, light of an amplifiable wavelength zone is fed to the optical amplification section in a range substantially not influencing the output of the ultraviolet light. Consequently, the influence of optical surges occurring when output of laser beams (ultraviolet light) is started is reduced. This enables a desired output to be regularly obtained.

Furthermore, the exposure apparatus of the present invention further includes the optical splitter section for splitting a laser beam generated by the laser light generation section into a plurality of laser beams, and the optical amplification sections are discretely provided for the plurality of the split laser beams. In addition, the wavelength modulator section collectively performs wavelength modulation in units of a bundle of laser beams output from the plurality of optical amplification sections. Thereby, the oscillation frequency of the output beam can be increased, the spatial coherence can be reduced, and the oscillation spectral linewidths can be narrowed overall with a simplified configuration.